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Applying Performance- Controlled Systems, Fuzzy Logic, and Fly-By-Wire Controls to General Aviation

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16. Abstract: A fuzzy-logic "performance control" system, providing envelope protection and direct command of airspeed, vertical velocity, and turn rate, was evaluated in a reconfigurable general aviation simulator (configured as a Piper Malibu) at the FAA Civil Aerospace Medical Institute. Performance of 24 individuals (6 each of high-time pilots, low-time pilots, student pilots, and nonpilots) was assessed during a flight task requiring participants to track a 3-D course, from take-off to landing, represented by a graphical pathway primary flight display. Baseline performance for each subject was also collected with a conventional control system. All participants operated each system with minimal explanation of its functioning and no training. Results indicated that the fuzzy-logic performance control reduced variable error and overshoots, required less time for novices to learn (as evidenced by time to achieve stable performance), required less effort to use (reduced control input activity), and was preferred by all groups.			
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APPLYING PERFORMANCE-CONTROLLED SYSTEMS, FUZZY LOGIC, AND FLY-BY-WIRE CONTROLS TO GENERAL AVIATION

BACKGROUND

In the opening of his book chapter titled *Pilot Control*, Sheldon Baron stated, "The importance of flight control to the development of aviation is difficult to overestimate" (Baron, 1988). Looking back through the history of aviation, we can see numerous efforts to make the human control of aircraft simpler, less variable, and more reliable. The 1970s was a particularly fertile period during which there was a great interest in efforts to simplify the manual control of systems, and one of those efforts was embodied in the "performance control system" (PCS) for aircraft (Bergman, 1976). This scheme allowed more direct control of performance parameters than did "conventional" systems and had the potential for eliminating undesirable aircraft behaviors and simplifying ab initio training. It is worth reiterating the history, as it still applies to general aviation (GA) aircraft, although some military and commercial air carrier aircraft employ what we could legitimately call performance-control logic.

The top-level goal for a flight is arrival at the destination. This can then be decomposed to subgoals, which involve the attainment of locations along the chosen path that can be used to assess progress toward the end goal. Progress toward these subgoals can then be directed by causing the aircraft to move toward those spatial subgoals, through manipulating ground track, altitude, etc. However, manual control of aircraft, using mechanical linkages in which control positions have a one-to-one correspondence with positions of the aerodynamic control surfaces, does not allow direct control of aircraft end-goal states. Rather, the pilot must effect changes in attitude and powerplant settings to cause changes in the higher-level performance variables. Turning to a specific heading, for example, requires the pilot to manipulate roll rate (aileron position) directly, to achieve a desired turn rate (indirectly), which will ultimately bring the aircraft to the desired heading. Mathematically, we have the pilot serving as at least a second-order integrator and, in some cases, a third-order integrator. (See Roscoe & Bergman, 1980; and Baron, 1988, for further discussion.)

A manual control task becomes easier to perform as its "order" approaches zero (Roscoe and Bergman, 1980), that is, when the human operator directly commands the end state of the system. We can achieve closer to a zero-order system in two ways. The most common means of accomplishing this in today's aviation environment is the autopilot in GA aircraft, or the Flight Management System (FMS) in corporate and scheduled carriers. In the simplest case of flying a heading, one sets the desired heading and the autopilot maneuvers the aircraft, at a specified limited rate of turn, to attain that heading. A second way in which we can achieve this result is to alter the control laws such that the pilot uses control position to command higher-level performance goals (for example, rate of turn/bank angle; rate of climb/descent), attaining a compromise between automated maneuvering and the authority inherent in manually guided maneuvering. There are two benefits that accrue from the latter approach. First, manual control is simplified relative to achieving performance-goal states. Second, safety is enhanced relative to conventional manual controls in that return of the self-centering (spring-loaded) side-stick to its centered position returns the aircraft to straight-and-level flight.

One should keep in mind that the gains seen with a PCS come at the expense of being unable to perform such maneuvers as barrel rolls and loops (requiring direct authority over control surfaces), which is not usually a problem in everyday GA flying. Recall that the PCS is commanding rate of climb and rate of heading change (via bank angle) directly, and thus any maneuver that would require a continuous non-zero pitch-change rate or bank-change rate cannot be performed. Previous research results from the GA environment using a PCS (Roscoe & Kraus, 1973; Bergman, 1976; Roscoe & Bergman, 1980) have indicated significant reductions in both mean and variable tracking error during the performance of navigation tasks, as well as a reduction in workload. These results were obtained both in a twin-engine simulator and in a conventionally instrumented Twin Bonanza with the PCS installed (controlled via a side-stick device), certified for normal flight operations with few procedural restrictions.

Stewart (1994) also examined, in a GA simulator, an implementation of a performance-control logic he termed the "E-Z Fly" control system for GA aircraft. Control was achieved through the normal control yoke, but the operator commanded vertical speed and rate of heading change. The throttle was used to command airspeed directly. The control logic contained limits on the commandable range of flight-performance parameters so that dangerous or unreasonable configurations could not be commanded by the operator. The control system was used in conjunction with a highway-in-the-sky-format (HITS) primary flight display, and gain of the controls was reduced on final approach to match the reduced width of the HITS pathway as it narrowed down to the runway width. Control forces were manipulated such that they were reduced to zero when the controls were moved to a new position and held there for more than a few seconds.

The results reported by Stewart were from 3 pilots and 7 non-pilots. Control of altitude, airspeed, and lateral error was better for both groups when the E-Z Fly system was engaged, and both groups exhibited less accurate path tracking during turns than during straight segments. Throttle-lever activity was reduced using the E-Z Fly system, and all of the participants preferred the E-Z Fly system over conventional controls.

Interest in applying simplified control schemes to GA aircraft reappeared with the government/industry Advanced General Aviation Transport Experiments (AGATE) program. Program goals included simplifying the flight task, reducing ab initio training requirements, and increasing the safety of flight. In the pursuit of these goals, an approach similar to the PCS was investigated in which a "fuzzy-logic" controller (FLC) was developed (Duerksen, 1996). Duerksen's goals were to create a "reusable" decoupled flight controller that could be directly installed on different airframes without the usual individual "tuning" associated with autopilot systems, and, with this fuzzy-logic system serving as an expert-systems supervisor, to provide control boundaries such as angle of attack and airspeed limits. Duerksen's efforts produced usable code that was then evaluated for its ability to control an aircraft by using simulation. The code was subsequently transported to the Advanced General Aviation Research Simulator (AGARS) at the FAA's Civil Aerospace Medical Institute (CAMI) for pilot performance evaluations.

METHOD

Subjects and Design

Twenty-four individuals (6 each of high-time pilots, low-time pilots, student pilots, and nonpilots) participated in the study. Each participant served as his/her own control, flying both the conventional yoke and the side-arm FLC so that control configuration was a within-subject variable. Each flight consisted of 9 discernable segments that were used as a second independent within-subject variable. Order of presentation of control type was counterbalanced across subjects. Dependent variables recorded included lateral and vertical course-tracking error (via digital recording), and control movements and blunder errors (via videotape).

Equipment

Data were collected in the AGARS configured as a Piper Malibu with a highway-in-the-sky format navigation display, using a follow-me airplane symbol and velocity vector on the copilot's side of the panel. The conventional system was flown with a back-loaded yoke and separate power controls. The FLC system was flown using 3 axes of a balanced, spring-centered and damped 4-axis side-arm controller (Figure 1; Beringer, 1999), with those axes representing turn rate (wrist rotation), climb / descent rate (vertical wrist flexion), and airspeed (fore-aft slide axis).

Procedures and Task

Following the signing of consent forms, participants were seated in the right seat of the AGARS for a short pre-flight briefing. The functioning and movement of the controller they were to use for that flight were described and demonstrated. Participants manipulated the side-arm control with their left hand, necessitated by structural restrictions on control and display placement, but were free to use either hand to manipulate the yoke. They were also shown the navigation display and given an explanation of its symbology and functioning. The simulator's engine was then started, and the flight was begun without any actual hands-on training in the use of the controls and displays. The experimenter, seated in the left seat, monitored the participant's progress and intervened only when it was necessary to limit extreme excursions of the simulator, to manipulate power in the conventional-controls configuration, or to prevent stalls or ground contacts. The pattern required a continuous climb from lift-off until the base-leg turn and then a descent on the approach.

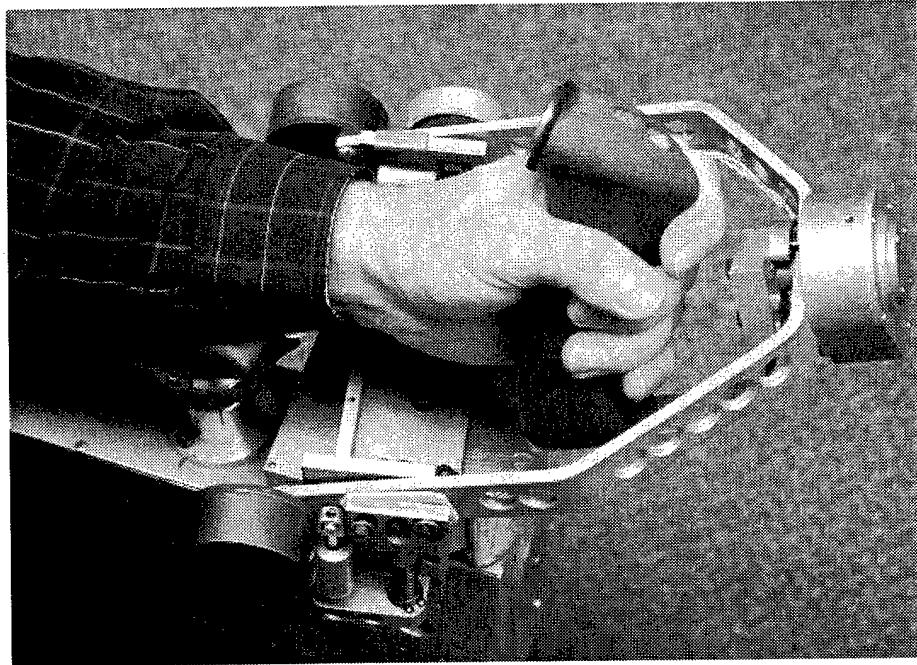


Figure 1. Four-axis side-arm controller used to implement the fuzzy-logic control inputs (Beringer, 1999).

The task required the participant to take off, establish a climb to intercept the pathway depicting the desired 3-D courseline, and follow the command guidance indicator (follow-me airplane) by aligning the aircraft velocity vector with the follow-me airplane. The subject was required to follow the command indications through a greatly extended pattern with a lengthened down-wind leg that turned back toward the airport (Albuquerque, runway 08) at the Albuquerque VOR and followed the instrument landing system (ILS) approach back to the runway. The flights ranged from 15 to 17 minutes. After a short break, the participant and experimenter discussed the functioning of the second controller to be used and performed a second flight with that controller. On both flights, the simulator entered actual instrument conditions on initial climbout and no external visual cues were available to the subject until breaking out just before landing. The session was concluded with post-test questionnaires about previous flight experience and about the participant's ratings of the 2 control systems.

RESULTS & DISCUSSION

Tracking Error

Analyses indicated that there were substantial reductions, as seen in the Bergman studies, in both mean and variable errors in the vertical and horizontal dimensions when the FLC was used, as compared

with the conventional controller (yoke). Overall analyses by group and control type indicated that use of the FLC produced less error, both horizontally and vertically (Figure 2). There were significant reductions in root-mean-square error (RMSE) for both vertical [$F(1,40)=18.11$, $p<0.0005$] and lateral [$F(1,40)=14.06$, $p<0.001$] and a shift in lateral bias (mean) error [$F(1,40)=21.09$, $p<0.00001$] (overall bias was to the left of courseline).

Much of the error reduction came in the turns, and Figures 3 and 4 show raw data plots for one nonpilot over the complete course. One can see in Figure 3 that the performance with conventional controls was far more variable, with the aircraft repeatedly flying through its commanded altitude. Figure 4 shows the lateral-error plot, and it also contains greater departures from desired track (and more variability) for the conventional control than for the FLC. One can also see where turns 3 and 4 were overshot considerably. These performance differences between control systems were consistent across all 4 groups of subjects, although the high-time pilots and 2 of the student pilots tended to fly more precisely, regardless of the type of control system used. Analyses also revealed some intraserial transfer (as found by Bergman), in that the conventional system initially fared worse if preceded by the FLC than when the conventional system was flown first. This effect dissipated over flight segments, however. No such effect was apparent for the FLC system. Overall, time to achieve stable

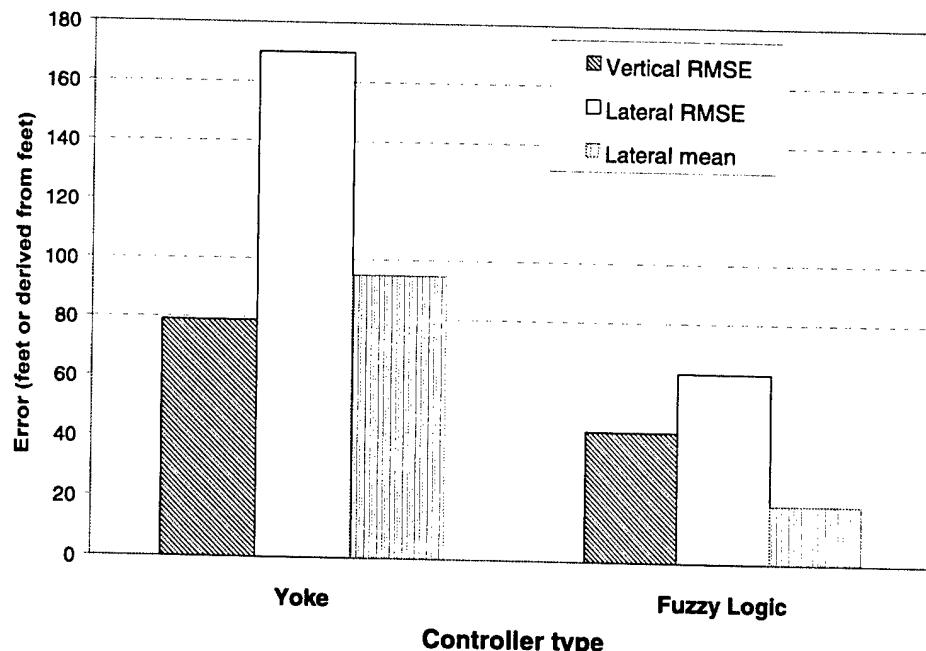


Figure 2. Main effects of control type for 3 measures of error.

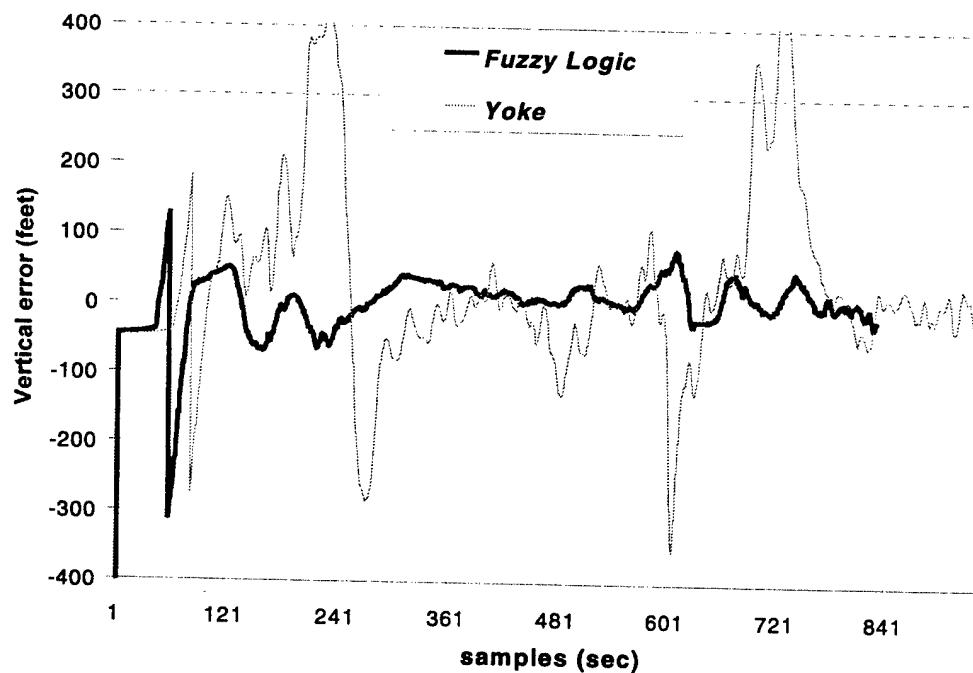


Figure 3. Plot of raw vertical error for 1 nonpilot.

performance was less for the FLC than for the conventional system. (The large spike at the beginning of the record is an anomaly in path error calculation that occurred prior to path capture.)

There were also the expected significant differences between the pilot groups (Figure 5), with the high- and low-time pilots exhibiting somewhat less error (lateral and vertical RMSE) than the nonpilots and student pilots [$F(3,40)$ for each: vertical mean, $F=3.22$, $p<0.05$; vertical RMSE, $F=5.23$, $p<0.005$; lateral RMSE approached significance, $F=2.8$, $p=0.0518$]. Group means are presented in Figure 5. No interactions between control type and pilot group were significant.

Control-Input Frequency

One could predict from an analysis of required control motions that the FLC should produce at least a 2:1 reduction in the frequency of observed control movements. That is, to enter and hold a given bank angle, the yoke requires at least 2 deflections (one to initiate and 1 to neutralize aileron at the desired bank angle), whereas the FLC requires a single deflection to the position corresponding to the bank angle (turn rate). Table 1 depicts data for 4 individuals, 1 randomly selected from each group (non-pilot, student

pilot, low-time pilot, high-time pilot), sampled for 30 seconds from Turn #1 (T1: crosswind leg), Turn #3 (T3: base leg), and final approach (App). With 2 exceptions in which the ratios are higher, the comparisons evidenced an approximately 3:1 reduction in control movements (defined as directional reversals) from the conventional control (Y) to the FLC (F). This measure can be thought of as an index of controlling workload, and the selected data shown are representative of the larger sample.

Participant Ratings

Participants rated each of the control systems for the degree of effort required during takeoff, climb, turns, level flight, descent/approach, and landing. The rating scale used 9 points from 1 (minimum effort) to 9 (maximum effort). Overall, the FLC was preferred over the conventional system (Figure 6), and participants rated the former as easier to use [$F(1,40)=34.73$, $p<0.00001$]. Those who were not pilots indicated that the FLC was easier to learn to use (Figure 6). Although there were some minor mean-rating differences between groups, pilot group was not a significant factor, nor was there a significant interaction between control type and pilot group.

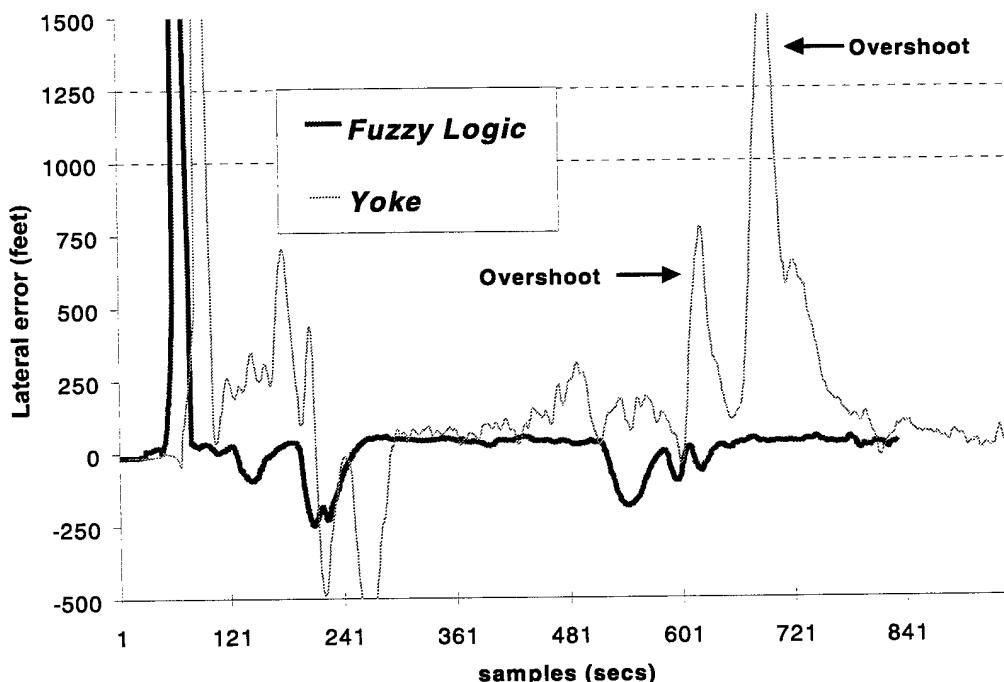


Figure 4. Plot of raw lateral error for 1 nonpilot.

Table 1. Frequency of control inputs by maneuver for 4 individuals, 1 from each pilot group.

		Turn 1		Turn 3		Approach		Means	
Pilot Type	Control Axis	Yoke	FLC	Yoke	FLC	Yoke	FLC	Yoke	FLC
Non	Pitch	na	na	10	0	4	5	7.0	2.5
	Roll	12	11	18	5	29	3	19.6	6.3
Stu	Roll	28	9	na	na	na	na	28.0	9.0
	Pitch	10	1	4	0	4	2	6.0	1.0
Low	Roll	24	12	20	7	24	5	22.6	8.0
	Pitch	8	0	8	1	6	2	7.3	1
High	Roll	11	4	16	6	10	2	12	4

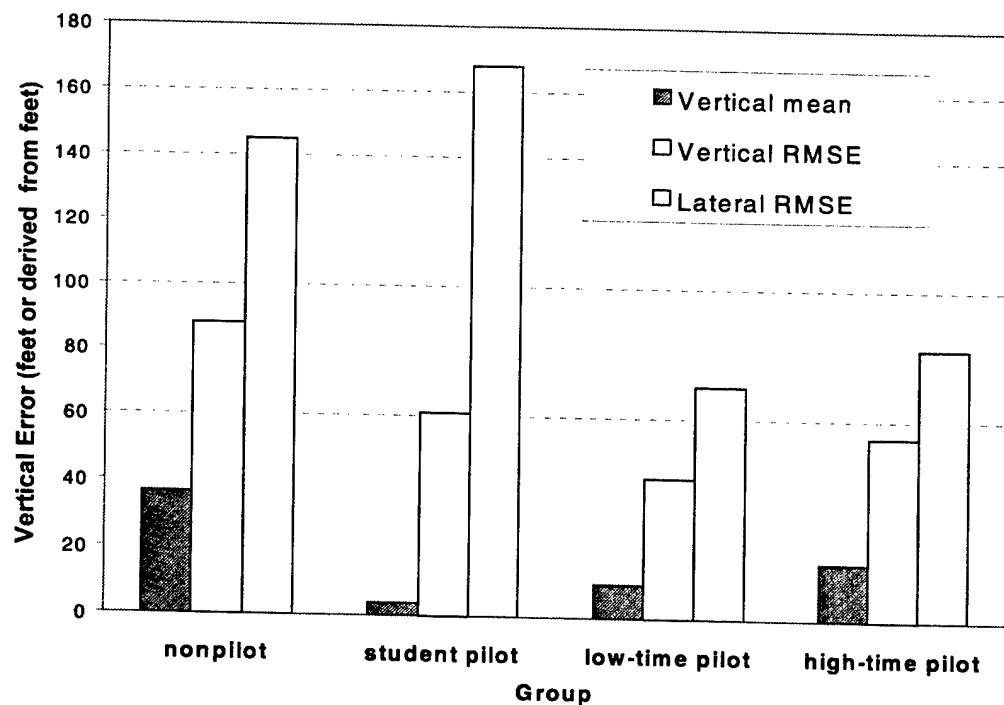


Figure 5. Three error measures by group.

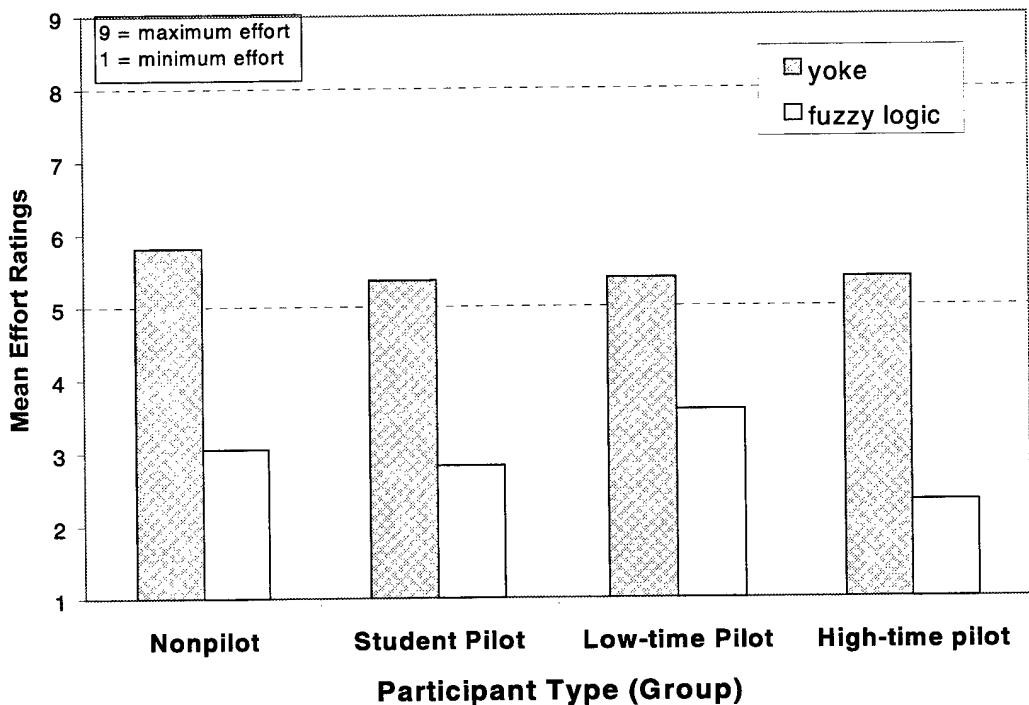


Figure 6. Mean perceived-effort ratings by group and control type.

When examined by flight segment, the biggest difference in ratings was found in the turns for all but low-time pilots. The one complaint with the FLC was the same as that in the Bergman studies. That is, users did not like having to hold the side-stick control deflected for long periods of time to maintain a climb or descent, although they rated it as "acceptable," due to a low spring force in that axis. This has since been addressed, and pilots can now "lock-in" desired performance and control position, thus alleviating the need to continually hold the control in the deflected position, coupled with a release mechanism triggered by force applied to the control.

Two additional observations are worth making regarding the results. First, there should not have been a significant effect of hand used for manipulating the FLC, in this case due to the low spring loading and comparatively low required input frequency. If there was an effect for the predominantly right-handed sample, then we are seeing the worst-possible case for this implementation. Second, the effect does not appear to be restricted to a specific display type, as earlier positive results (Bergman) were obtained with conventional instrumentation.

CONCLUSIONS

The findings were consistent with previous PCS studies, indicating that the FLC system can provide stable and less variable course and altitude tracking performance than a conventionally configured system when used as a manual control. This makes the system a potential alternative for next-generation GA aircraft from pilot-performance and pilot-training standpoints. However, there are 2 considerable concerns that must be addressed prior to application in a production aircraft. First, the cost of the system must come down to the point where it is an economic competitor with other means of aircraft control (meaning affordable and certifiable control computer, servos, etc.). Second, the debate must be resolved over reliability and reversion modes and their effect upon training. If the system is to be implemented in a class of aircraft where no other means of control will be available as a back-up (only 1 type of control is trained), reliability must be sufficiently high. If, however, a reversion mode is provided to allow for a slightly less reliable FLC, then one either adds the cost of redundant identical systems, or one employs a stand-by mechanical linkage system and incurs the cost and complexity of training the pilot to operate *both* types of control systems. Again, it ultimately comes down to where one wishes to incur the cost for potentially increased safety and ease of operation.

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